Erodibility and Stability of Tidal Flats: Characterization and Prediction

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LONG-TERM GOALS

To improve our capabilities for measuring and predicting erosion rates, sediment flux, water clarity and bed strength in muddy coastal environments, including variations in space (e.g., flats vs channels) and time (e.g., seasonal variations).

OBJECTIVES

The broad objectives of my work in the Tidal Flats DRI were to:

1) Quantify erodibility of sediment in a muddy mesotidal flat-channel complex in southern Willapa Bay and its seasonal variations.
2) Correlate temporal and spatial variations in erodibility with other sediment characteristics.
3) Use the results to investigate and improve sediment transport models of intertidal environments.

APPROACH

Measurements of erodibility, porosity and sediment size were made three times during a year (2009-2010) at sites within a muddy, mesotidal flat-channel complex in southern Willapa Bay, WA. We measured erosion rates using two Gust erosion chambers (Brent Law operated one, I operated the other) that fit on a core tube and use a calibrated, rotating upper plate to generate a flow with a specified shear stress on the sediment surface. Erosion tests were run at stresses of 0.01 (an initializing step not used in the subsequent analysis), 0.08, 0.16, 0.24, 0.32 and 0.4 Pa; each shear stress was maintained for 20 min and then increased. If the applied shear stress exceeded the critical shear stress at the bed surface, turbidity increased quickly and then gradually decreased back toward background conditions as the turbid water was pumped out and replaced with ambient water. Water leaving the chambers was collected in bottles, filtered, dried, combusted and weighed to obtain eroded inorganic sediment mass. Average critical shear stress profiles, the metric we used for erodibility, were quantified using a power-law fit to cumulative eroded mass vs. shear stress for the flats and channel. Laboratory erosion measurements of deposits made from slurries of flat and channel sediment quantified erodibility over consolidation time scales of 6-96 hrs. Modeling of sediment transport in

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flat-channel and marsh-channel complexes was done (with postdoc Ilgar Safak, who received 4 months of support in FY12 from this grant) using Delft-3D, a suite of models for calculating hydrodynamics, sediment transport and morphologic change in response to tidal and meteorological forcing.

WORK COMPLETED IN FY12

1. Revisions to manuscript submitted to Continental Shelf Research special section on the Tidal Flats DRI studies: Wiberg et al. (2012).
2. Analysis of grain size of sediment eroded during erosion tests (in collaboration with Brent Law).
3. Implementation and model calculations using Delft3D of tidal flow and sediment transport in a secondary tidal channel-flat complex like those in southern Willapa Bay.
4. Results of model calculations for Willapa Bay and comparison to a micro-tidal salt marsh environment were presented at the 2012 AGU/ASLO Ocean Sciences Meeting.

RESULTS

Observations

Summer and winter measurements of erodibility and related sediment characteristics revealed that the tidal flats were well consolidated and characterized by persistently low erodibility despite significant seasonal variations in biological activity on the flats. The bed of the secondary tidal channel adjacent to the flats exhibited relatively high erodibility in winter and low erodibility, comparable to that of the flats, in summer. Comparison with laboratory measurements of erodibility and consolidation suggests that high winter channel-bed erodibility was associated with a partially consolidated bed. The channel flanks mediate the exchange of sediment between the channel and flats. Sediment on the northern (left) channel flank maintained relatively high erodibility year round, whereas sediment on the southern flank did not.

The erosion measurements allow us to determine the parameters in a standard erosion rate equation of the form $E=M(\tau_b - \tau_{cr})$, where E is erosion rate, τ_b is the bed shear stress due to the flow, τ_{cr} is the critical shear stress for mobilizing the sediment, and M is a coefficient. Values for τ_{cr} (as a function of depth for cohesive sediment) and M generally cannot be predicted for cohesive sediment in the absence of site-specific observations, but can be determined from the erosion-rate data. Measurements of the size distribution of sediment eroded in the Gust chamber at each shear stress reveal that size distributions in the channel and flats in winter and summer do not evolve as shear stress increases (Fig. 1), consistent with cohesive sediment behavior (Law et al, 2008). Power-law fits to cumulative eroded mass vs. shear stress provide general relationships for critical shear stress as a function of eroded mass and near-surface bed porosity (2-4 mm below the sediment surface). Estimates of the coefficient M are on the order of 10^{-4} - 10^{-3} s/m.

Our quantitative relationships for critical shear stress as a function of eroded mass and near-surface bed porosity provide important constraints on sediment availability in models of tidal flat morphodynamics. These relationships can be used to make simple estimates of suspended sediment concentration (SSC) under given flow conditions (bed shear stress and water depth) assuming that the mass of sediment available for resuspension at any time is supply limited and controlled by these relationships – assumptions that will overestimate resuspension if erosion is rate limited rather than

supply limited. Based these assumptions, we estimated values of SSC during peak tidal flows in the channel of ~ 0.02 g/L in summer, consistent with observations, and of 0.13 g/L during late winter conditions. Observations from other investigators (e.g., December water column measurements of peak flood SSC of ~ 0.5 g/L from Nowacki and Ogston (2012)) suggest that the channel bed had a larger supply of erodible sediment in early winter, possibly due to higher wind conditions, rainfall, and river (and sediment) discharge. These results, together with my parameterization of the erosion rate equation, suggest that SSC and sediment fluxes on tidal flats and in the channel during summer are supply limited owing to consolidation and cohesion. Erosion of more mobile, winter deposits in the channels may be rate-limited rather than supply limited.

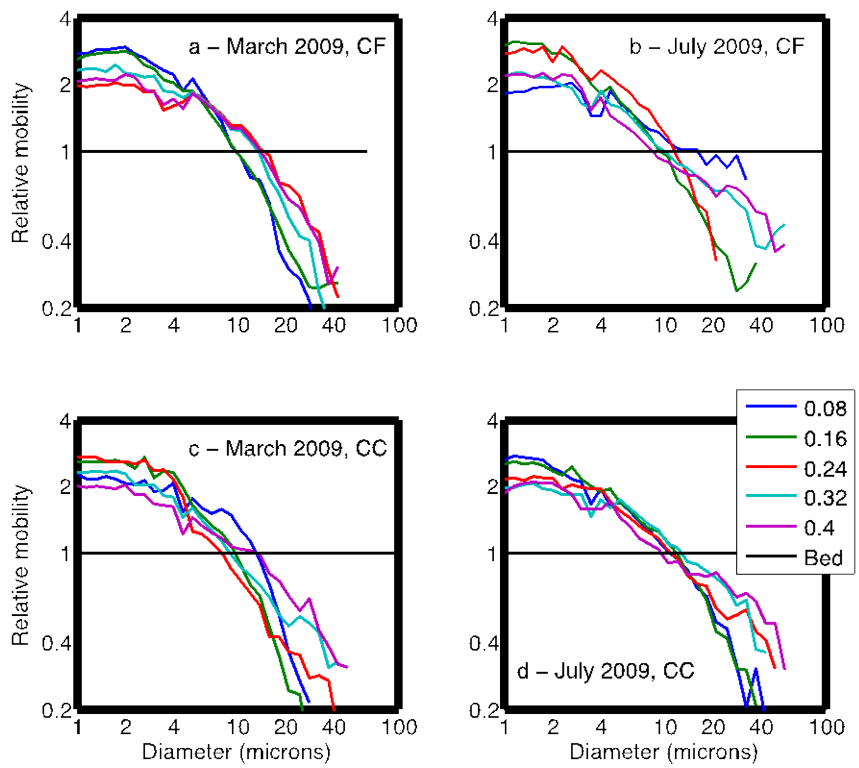

Figure 1. Size-specific relative mobility, obtained by dividing the disaggregated inorganic grain size (DIGS) distributions for sediment in the effluent water collected during each stress step by the size distribution of the bed surface for C-Flat in a) March 2009 and b) July 2009 and for C-Channel in c) March 2009 and d) July 2009. The black line at a relative mobility of 1 represents bottom sediments that erode equally from the seabed. Sizes with relative mobilities > 1 (<1) are over- (under-) represented in the water column relative to their presence at the bed surface.

Modeling

Our implementation of Deflt3D (open-source version) on a simplified grid for mesotidal flat-channel complexes like those in Willapa Bay (Fig. 2) yields velocity and SSC time series (Fig. 3a) in reasonable agreement with values measured by other investigators (e.g., Nowacki and Ogston, 2012). Values of vertically averaged current speed and SSC as a function of water level show peaks just before the flats are drained on ebbing tides and just after they are flooded on flooding tides, consistent with observed pulses in current speed and SSC (Fig. 4). Sediment resuspension in Delft3D, for a given

bed shear stress, is controlled primarily by settling velocity and an erosion rate parameter, ER ($=M^*\tau_{cr}$); critical shear stress must also be specified but it is not allowed to vary with depth or mass eroded. A total limit on sediment supply can be set in Delft3D, but not one that varies as a function of applied shear stress. SSC in the model calculations is more sensitive to the erosion rate parameter than to settling velocity. For a reasonable estimate of settling velocity of 0.5 mm/s (assumes flocculated particles), peak channel SSC during a 2-week period of tidal flow ranges from 1.2 g/L for ER = 3×10^{-5} kg/m^2/s to 0.1 g/L for ER = 3×10^{-6} kg/m^2/s. While a value of ER intermediate within this range, e.g., ER = 1×10^{-5} kg/m^2/s (Fig. 3), provides reasonable estimates of SSC in secondary channels in Willapa Bay, the simple erosion rate formulation in Delft3D cannot account for reductions in erosion rates as more easily eroded sediment is removed from the channel leaving a more consolidated deposit.

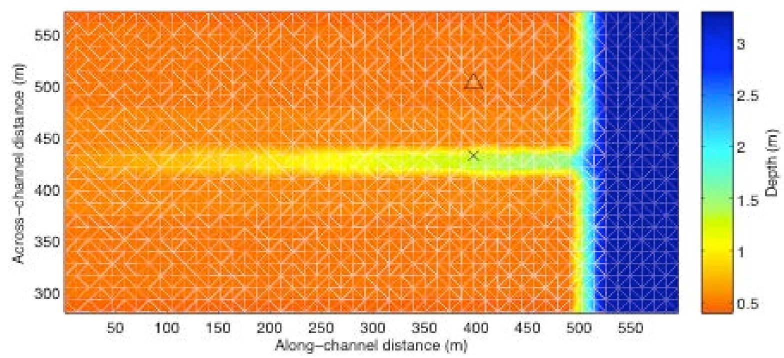

Figure 2. Model domain for tidal flat-channel flow and sediment transport simulations using Delft3D. The smaller channel (our focus) is about 1-m deep in the region near its intersection with the larger tidal channel. The flats are about 0.5-m below MSL. The symbols indicate locations where time series were saved from the model runs (e.g, Figs. 3 and 4).

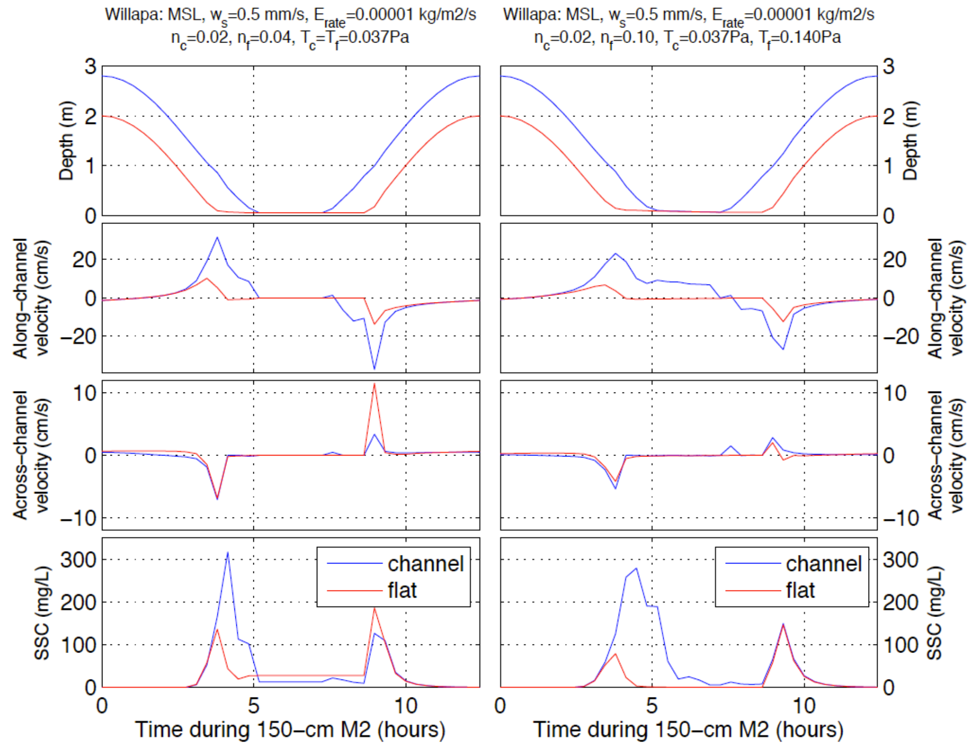

Figure 3: Time series of calculated water depth (top), along-channel velocity (2nd panel), across-channel velocity (3rd panel) and suspended sediment concentration (bottom panel) over a tidal cycle assuming a settling velocity of 0.5 mm/s and an erosion rate parameter of 1×10^{-5} kg/m^2/s. The left panels correspond to unvegetated flats like those found currently in Willapa Bay. The right panels consider a case with increased flat roughness and critical shear stress such as might accompany the appearance of marsh grass on the flats.

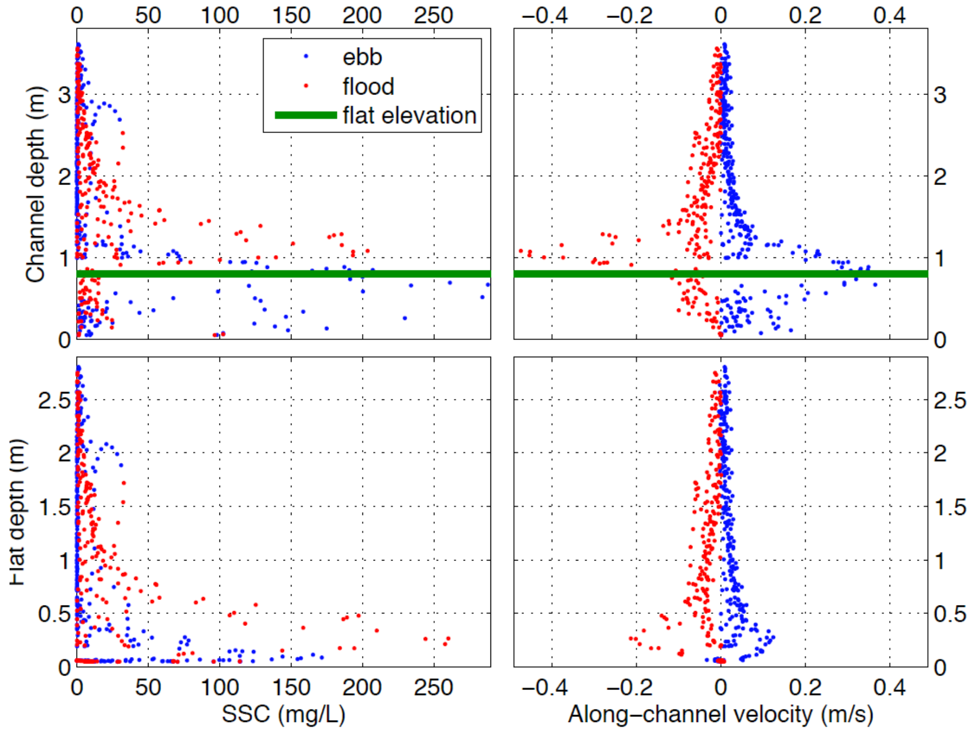

Figure 4. Plots of vertically averaged along-channel velocity and suspended sediment concentration (SSC) as a function of flow depth on the flats and in the channel during flood and ebb tides. The level of the flats is indicated by the green line. A pulse of velocity and SSC are predicted when water levels just overtop the flats, consistent with observations.

We carried out a number of sensitivity tests of calculated flow and SSC in addition to varying ER and settling rate. In particular, we considered the effect of tidal range and flat characteristics on flow and SSC. For example, results are shown in Fig. 3b for a case in which flat roughness and critical shear stress are increased in an effort to simulate flow and SSC if the flats in Willapa Bay were to become vegetated with marsh grass – a threat that is very real in Willapa Bay. Preliminary results indicate that high marsh roughness and critical shear stress are not sufficient to represent the effects of marsh grass on flow and sediment entrainment. Nevertheless, the model clearly provides a useful tool for better understanding the common and distinct dynamics of a range of intertidal environments. Our current modeling effort is focused on ways to improve our ability to incorporate our knowledge of erodibility into Delft3D. However, we may also consider switching to a coastal model that provides more flexibility in the way that sediment entrainment is calculated, such as the version of ROMS that incorporates the USGS sediment transport algorithms.

IMPACT/APPLICATION

- Quantification of the role of spatial and seasonal variations in erodibility on tidal flats.
- Better understanding of the role of time-dependent sediment availability and consolidation on tidal-flat sediment erosion.
- Numerical modeling of tidal flat sediment transport and morphologic evolution.

RELATED PROJECTS

None

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PUBLICATIONS

Wiberg, P.L., B.A. Law, R.A. Wheatcroft, T.G. Milligan and P.S. Hill, 2012. Seasonal variations in erodibility and sediment transport potential in a mesotidal channel-flat complex, Willapa Bay, WA. Continental Shelf Research, doi: 10.1016/j.csr.2012.07.021.

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